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An Improved Method for GPS-based Network Position Location in Forests[1]

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***Abstract*—In this paper we present a technique for improving the location performance based on the Global Positioning System (GPS) for networks of nodes in harsh environments and demonstrate its efficacy via a combination of simulations and measurements in forests. The technique relies on the use of Ultra-wideband (UWB) signals to measure time-of-flight (TOF) and consequently the range between nodes to improve localization in harsh forest environments. Specifically, we create a system of range equations based on network connectivity and solve this system of non-linear equations using a Least-Squares Non-Linear optimization technique using any available GPS information as the initial estimate. Based on our simulations and measurements, the improved technique results in a localization accuracy in forests that is on par with clear-field reference GPS measurements.**

Index Terms— **Global Positioning System, Least squares estimation, Localization, UWB, Non-linear optimization**

I. INTRODUCTION

THE Global Positioning System (GPS) is designed to provide accurate position estimates in clear, line-of-sight (LOS) locations where several satellites are in view and little degradation (e.g., multipath) in the signals is observed. An ideal GPS environment consists of a field or brush area with an unobstructed, overhead view of the sky. However, GPS is now being applied in newer industries and applications (e.g., farming, warfare, emergency services, and personal location), many of which have less-than-ideal environments but still require accurate positioning. Some of these less-than-ideal environments include indoor-areas, forests, and urban locations. Problems in these areas arise due to significant multipath interference, LOS signal obstruction, poor received-satellite geometry, or a combination of these effects. These common forms of interference have a significant impact on GPS positioning because of the normally low received GPS signal-strengths. By combining GPS with some other positioning technology which is robust in harsh environments, it is possible to improve the positioning capability of a network of nodes. Impulse-based Ultra-Wideband (UWB) is one such candidate technology. UWB can be used to measure the distance (via time-of-flight or TOF measurements) between two or more GPS receivers in a harsh, possibly non-LOS environment, which can then be used to improve the GPS position estimates. UWB signals are defined by the FCC as a signal having a bandwidth greater than or equal to one-fifth of its center-frequency; or, a total bandwidth of more than 500 MHz [1]. Impulse-based UWB signals consist of short-duration (typically low duty cycle) pulses with very low power spectral density. The short duration of the pulse makes the UWB signal more robust in harsh multipath environments, since the reflected components of the signal typically do not interfere with the first-arriving pulse. Additionally, UWB is able to penetrate light obstacles such as interior walls of buildings and forest-foliage [2]. Because of these properties, impulse-UWB has an advantage over traditional narrowband signals in position-location applications [2]. UWB also allows for spectral overlay, precise time-of-flight measurements, and low power, all while maintaining the signal's robustness.

This paper evaluates the effectiveness of using UWB-based signals to aid in the positioning of a network of GPS-enabled nodes. More specifically, the set of measured distances between nodes establishes a system of non-linear equations which can be exploited to determine the node locations. We utilize a non-linear optimization technique to solve the system of non-linear equations employing the GPS measurements as an initial guess of the solution. Thus, using the original GPS location estimates combined with ranging information we are able to achieve a more accurate position estimate.

In Section II we will briefly describe a subset of previous investigations into UWB-based positioning. Section III describes the network model assumed and the error metrics and outlines the notation used throughout this work. This work is based on a combination of measurements and computer simulations. Section IV provides a description and the results of the GPS measurements taken in this work including measurements in clear-field locations and in various forest environments. UWB measurements were also taken to establish the ranging capabilities of UWB signals. These measurements are described in Section V. The proposed algorithm for improving position location is presented in Section VI. Section VII provides performance results based on computer simulations and the measurements described in

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TABLE 1. GPS PRECISION IN VARIOUS ENVIRONMENTS

Environment	Std. Deviation (m)	Average Error (m)	Min Error (m)	Max Error (m)
Clear Field (reference)	0.50817	1.0732	0.12031	2.409
Light Forest 1	5.0842	7.7551	1.3639	18.565
Light Forest 2	5.503	8.2025	1.379	22.415
Medium Forest	6.2097	9.6826	1.4822	26.0957

Sections IV and V. Section VIII provides conclusions.

II. PREVIOUS UWB POSITIONING WORK

From previous research involving UWB-based positioning, the precision of the reference measurements is critical. Research conducted at the University of Tennessee involving indoor 3D-positioning radar used an optotrak system to place antennas and receivers with sub-millimeter accuracy [3], and as a result they were able to confirm the use of UWB ranging to measure sub-centimeter ranges accurately. Others (specifically [3], [4], and [5]) have established that the effects of multipath interference and light LOS obstructions on UWB signals for both ranging and data transmission are very low. Yu and Opperman proposed a UWB-positioning system based on mobile "tags" which are referenced to known receiver locations [6]. Their work is similar to the research highlighted in this paper, but differs in the fact that their system relies on having manually defined positions for the receivers. A majority of the recent work on position location for networks of nodes (e.g., [7],[8],[9]) relies on measurements to known anchors and uses the position of the anchors combined with the range/angle measurements. Our current work differs from the majority of existing work in that (a) it is a means for improving GPS, (b) it utilizes non-linear optimization for determining position, and (c) we provide measurement data along with our simulation results to establish the efficacy of the approach.

III. SYSTEM MODEL AND SET-UP

In this work we assume a network of *N* nodes each equipped with a GPS receiver and a UWB transceiver deployed in a forest (or some other harsh environment) as shown in Figure 1. We assume that the nodes (or a majority of the nodes) obtain initial estimates of their position based on GPS. Due to the foliage and ground cover, some nodes may not be able to obtain their position estimate while others will likely have poor estimates. The position of the *i*th node in two dimensions is represented by the two-dimensional vector $\mathbf{x}_i=[x_i,y_i]^T$. The estimated position of the *i*th node is represented by $\hat{\mathbf{x}}_i$ and the error in the estimate is represented by $e_i = \left\|\hat{\mathbf{x}}_i - \mathbf{x}_i\right\|$ where $\left\|\mathbf{y}\right\|$ is the norm of the vector $\mathbf{y}$. For this study, we assume that all of the nodes are stationary. Once the nodes have independently determined (or attempted to determine) their position via GPS, they obtain range estimates using TOF measurements based on a packet handshake. Only those nodes that are within communication range of each other (represented by the dashed lines in Figure 1) obtain these estimates. In this study we assumed the use of a UWB physical layer. The resulting range measurements are then used to improve the GPS measurements as described in Section IV.

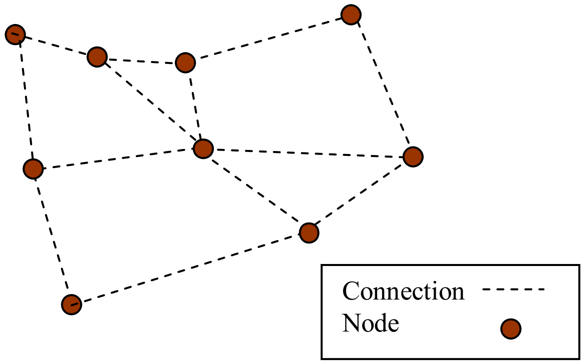

Figure 1. Example sensor network assumed in this work

IV. MEASURED GPS PERFORMANCE

The work presented in this paper is based on a combination of measurements and simulation. In order to establish the accuracy of the overall system, we must first determine the accuracy of the GPS component which provides the initial estimates. To determine the accuracy of GPS in a forest (the harsh environment of interest in this work), measurements were taken in the Jefferson National Forest near Blacksburg, Virginia in a variety of conditions.

The GPS receiver used to measure GPS precision was a Garmin GPSMap 60Cx – a high-end, consumer-grade handheld. Because this was an off-the-shelf consumer product, the GPS unit provides a black-box style interface with the internal details hidden. In order to overcome not having a known reference, it was decided that averaging multiple points in a known pattern (e.g., in a square) would yield a pseudo-reference, assuming the measurement errors were unbiased. Each measurement set consisted of 40 measurements around a 50m by 50m square-pattern, with measurements taken every 5 meters. The measured GPS data points were then fitted to the square using least-squares, which provided estimates for average error and the standard deviation of the error. Results from these measurements are shown in Table 1. The error was calculated as the Euclidean distance between the GPS provided location and the 'true' location. Specifically, $e_i = \left\|\hat{\mathbf{x}}_i - \mathbf{x}_i\right\|$. As can be seen from Table 1, there was little difference between various forest environments as compared to the degradation between a forest and a clear field. Specifically, the measurements in a clear field were within 1m of the 'true' location whereas the average error measured in a forest ranged from 7.8m in a light forest to 9.7m in a medium forest.

V. MEASURED UWB PERFORMANCE

In order to characterize the potential accuracy of UWB-based ranging, measurements were taken using both a computer-controlled-track and tripods. The 3GHz wide UWB signal was produced using a Tektronix AWG7102 Arbitrary Waveform Generator followed by a 50W Class-A power amplifier into either a Horn- or Bicone-style antenna. The transmit power was fairly high and would require pulse averaging to replicate in practice. A Tektronix DPO70804 Digital Phosphor Oscilloscope (DPO) proceeded by a low-noise-amplifier connected to a Horn or Bicone antenna was used to measure the transmitted signal. The DPO was configured to sample at 25 GS/s. A reference measurement was taken with the receiving antenna placed at a short distance from the transmitting antenna for calibration purposes. The expected TOF was then calculated using the known-distance. The system delay was determined by subtracting the expected TOF value from the total time. This system delay was applied to all subsequent measurements in order to determine TOF.

All but one of the forest measurements were taken with a track placed parallel along a path from 5m to 50m away from the transmitter. The transmitting antenna was fixed in place on top of a tripod, and the receiver was moved in 60 incremental steps of 2cm along the track (accurate to ±10 μm). The track was moved either 2m or 5m between measurements. For the designated TOF measurement, a 24m by 24m grid with 9 points was mapped. Due to time constraints, a tripod was used for the receiver instead of the track. During this measurement set it became apparent that there would not be enough precision in terms of placing the equipment in order to make the results useful. The mapped-out-area for the designated TOF measurement had up to 30cm of error in one point, which is extremely significant compared to the expected errors of approximately 2.4cm. It was concluded that it would not be feasible to manually configure a grid with the needed precision, especially in an environment consisting of uneven ground and fallen trees. Thus the earlier measurements involving the track were used to determine the precision, and a secondary reference set of measurements was taken in a highly controlled environment (a uniform hallway) to determine system delays at various distances. The results of all of these measurements, shown in Table 2, give an average standard deviation of approximately 7mm. Note that the signal-to-noise ratio in these measurements was fairly high, due to the equipment used. The SNR of an actual application would depend on the update rate of the system and the power limits of UWB transmissions. These measurements would correspond to a fairly slow update rate and represent a lower limit on the error.

TABLE 2. UWB PRECISION AT VARIOUS DISTANCES

DISTANCE (M)	STD DEV (M)	MAX ERROR (M)
4.5m	0.005883	0.015435
5m	0.006693	0.023195
10m	0.006886	0.02751
15m	0.005856	0.031203
20m	0.007065	0.027261
30m	0.006533	0.019294

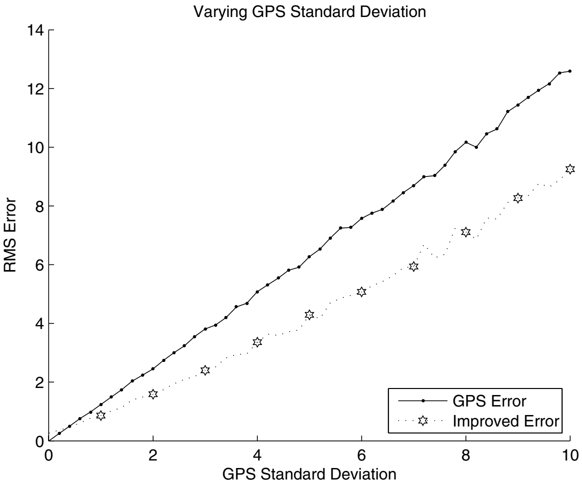

Figure 2. Impact on the performance of the standard

VI. IMPROVED POSITION ESTIMATION ALGORITHM

A key to improving *network* localization performance when relying on GPS for position information is the fact that the nodes' positions must satisfy certain constraints based on the distances between nodes. Specifically, given the set of UWB range measurements, the positions of the nodes ideally must satisfy the following set of non-linear equations:

$$r_{12}^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2$$

$$\vdots$$

$$r_{mn}^2 = (x_m - x_n)^2 + (y_m - y_n)^2$$

for all nodes *m* and *n* in communication range of each other.

However, this assumes that we know the distances between nodes exactly. Given that the estimates are noisy, we cannot solve the above set of non-linear equations exactly. Thus, we seek a solution $\mathbf{z} = [x_1, y_1, x_2, y_2, x_3, y_3, \ldots x_N, y_N]$ that minimizes the square error. That is we want to find

$$\mathbf{z}_{opt} = \min_{\mathbf{z}} \sum_{i,j} \left[r_{ij}^2 - (x_i - x_j)^2 - (y_i - y_j)^2 \right]^2$$

To solve this non-linear optimization problem, we used the Levenberg-Marquardt algorithm, an iterative technique which combines the method of steepest descent and the Gauss-Newton method. As with most iterative solutions, the quality of the initial solution is important for non-linear optimization problems. In this work we use the GPS-provided position information as the initial solution.

VII. SIMULATION RESULTS

To determine the efficacy of the approach described in the previous section, simulations were used to measure the accuracy in terms of Euclidean distance error. For the simulations it was assumed that the true locations were distributed randomly in a square area (100m x 100m), and that the GPS errors were zero-mean Gaussian (in x and y coordinates) defined by some standard deviation. UWB ranges were simulated as Gaussian noise error plus a uniformly distributed bias to represent non-line-of-sight measurements as appropriate. The error parameters were derived from the measurements. All simulation parameters are shown in Table 3.

TABLE 3. STANDARD SIMULATION PARAMETERS

Number of Nodes	20
Square Area Width	100m
Maximum Range Limit	25m
Std. Dev. Of GPS Error	5m
Std. Dev. Of UWB Error	0.01m

The simulations represent a typical large-area (100m x 100m), low-node-density configuration. The number of nodes, area size, and maximum range limit all directly contributed to the overall connectivity of the system and thus impacted performance. In the case where a node is not connected to any other nodes and thus could not improve its position estimate, the GPS position estimate is used. Figure 2 corresponds to the observed accuracy of the original (i.e., GPS) and the improved system as the quality of the environment (specifically the GPS accuracy) worsens. Figure 3 shows the impact of increasing the UWB ranging error. Clearly increasing the error in either measurement degrades overall accuracy. However, the improved system shows more robustness to increasing GPS error as was anticipated. Clearly, the UWB ranging error does not have any impact on the original GPS measurements. Figures 4, 5, and 6 each examine the impact of connectivity on the performance of the proposed system. As the number of sensors or the communication range increases, more information is available to correct GPS errors and thus the performance improves. As the area increases (Figure 6), the performance degrades since connectivity will suffer for a fixed node communication range. However, together the figures show that for moderate values of area size, communication range, and node density substantial improvements in localization accuracy are achievable. Specifically, we can see in the figures that although the rms error is approximately 5-8m in a forest using GPS only, the error can be reduced to less than 2m (nearly 1.5m) using ranging between nodes. This is nearly the accuracy achievable in clear-sky conditions.

As a final comparison, we examine the impact of NLOS errors on the performance of the proposed technique. The plot in Figure 7 shows the performance of the scheme when there is a 5m NLOS bias present in a varying percentage of the nodes. We can see that even in the presence of a large bias error the performance improves unless 80% of the ranges are biased.

VIII. CONCLUSIONS

The results of the simulations, shown in Figures 2 through 7, indicate that even with limited ranging information, position location can still be improved using range information between GPS-enabled nodes. Increasing the number of sensors or the communication range improves the solution, while increasing the area size or the error in the UWB-ranging or GPS-positioning worsens it. It should be noted that the number of sensors, range limit, and area size will not cause the improved solution to be less accurate than the original GPS solution. As long as the UWB ranging is reasonably accurate, the results of the optimization will always be better than GPS positioning alone. For more ideal situations such as small-area, high node-density configurations, the optimized solution will be greatly improved over standard GPS. In such a case, performance in a forest can rival open-field clear-sky GPS measurements.

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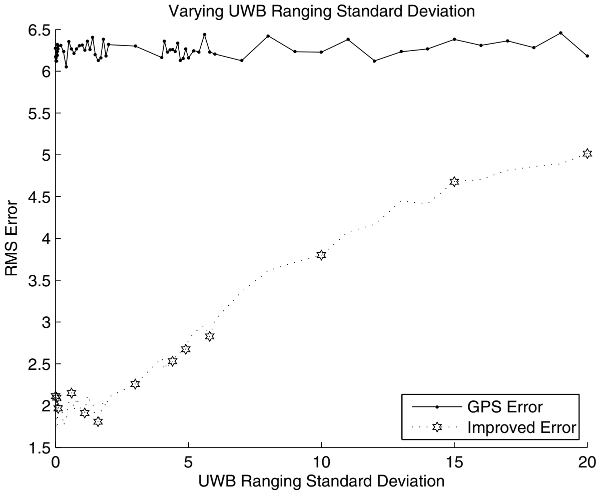

Figure 3. Impact of the standard deviation of the ranging error on the localization error

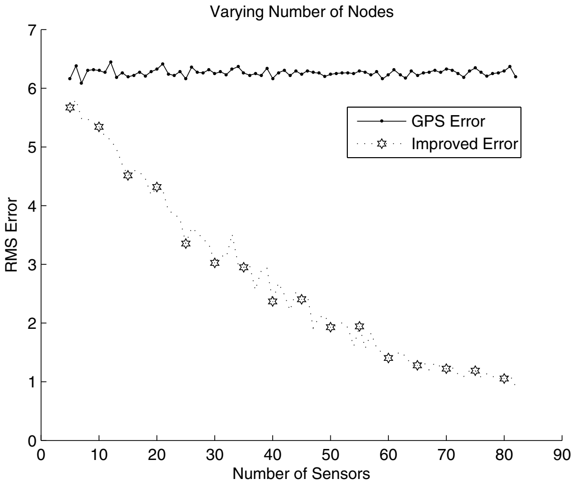

Figure 4. Impact of varying the number of nodes on localization performance

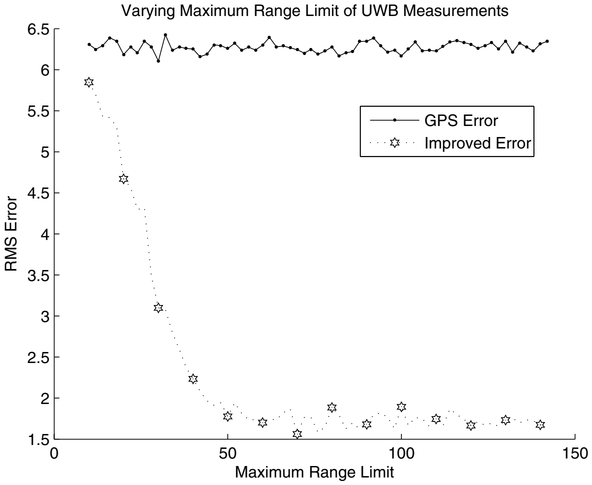

Figure 5. Impact of varying the maximum range of UWB communication.

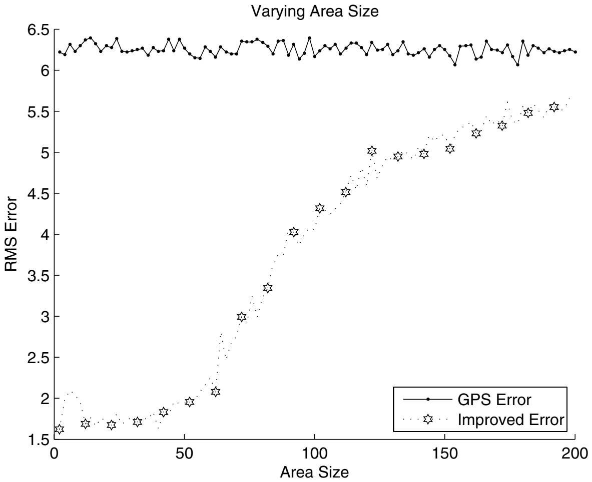

Figure 6. Impact of the area size on localization error

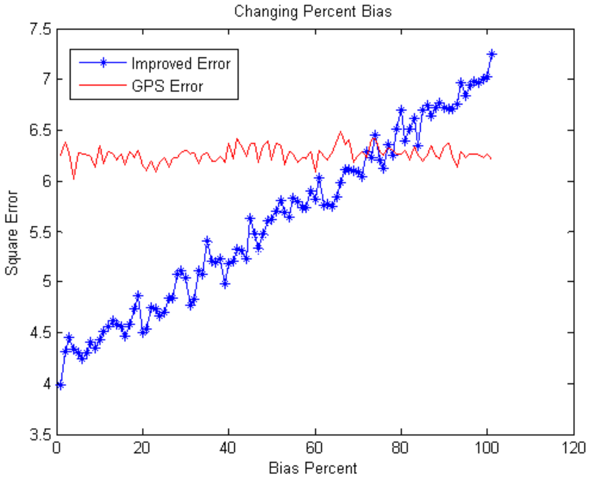

Figure 7. Impact of NLOS error on localization error